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DISCUSSION OF WIND-LOAD STANDARDS IN EUROPE

(Published in November, 1950)

By Paul Rogers, Carl H. Walther, Francis L. Castleman, Jr., and Aron L. Mirsky, S. K. Ghaswala, Herbert S. Saffir, Theodore B. Rights, and John W. T. Van Erp

STRUCTURAL DIVISION

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DISCUSSION

PAUL ROGERS,[9] M. ASCE.—It has been known to engineers for a long time that the customary wind pressures applied in the design of structures are not in accord with the actual wind-forces. By presenting several wind-load standards of various European countries, the author gives a worthwhile contribution to the engineering literature.

The writer is at variance, however, with the author's opinion that the possibility of resonance between the frequencies of wind and structure need not be investigated. The author himself refers to a paper[4] that deals with exactly such occurrences.

A few years ago the writer was called upon to investigate the strange behavior of a large smokestack, second in a row of four stacks. The stack in question underwent considerable deflections, perpendicular to the wind direction, during moderate wind velocities, whereas it was perfectly stable at high wind velocities. No faults could be discovered with the statical computations or structural design of the stacks. Subsequent analysis has proved the possibility of resonance between the periodicity of the eddies shed in the wake of the first stack and of the natural period of vibration of the second stack, when the wind was blowing from a certain direction at critical wind velocity. The stack vibrations were finally eliminated after the installation of the lining, which substantially changed the natural frequency of the stack. As a result of investigations, it was deemed advisable to adopt, as a design standard, the stipulation that the spacing of smokestacks should not fall within the critical range, that is, between $3\frac{1}{2}$ to $5\frac{1}{2}$ times the stack diameter.

CARL H. WALTHER,[10] Assoc. M. ASCE.—A useful service has been rendered in presenting this summary of the pressures and coefficients for wind loadings in use in various European standard codes. It is all too true that, as the author states (under the heading "Introduction"), "In most building codes in the United States, obsolete conceptions of wind load still prevail * * *." Even among practicing engineers similar primitive conceptions of the magnitude and distribution of wind pressures remain common in spite of the numerous publications that have dealt with the subject over the past twenty-five years. Any attempt to bring the well-established principles governing wind pressure to the attention of a large part of the profession is to be applauded.

The writer notes that the present paper does not include information on the location of the resultant wind force for wind directions oblique to the walls of a building. It is well known that the center of pressure on a plate oblique to the direction of the wind does not coincide with the geometrical centroid of the area but is displaced toward the leading edge of the plate.[11] A similar effect is observed in wind-tunnel tests of models of buildings with the wind at

NOTE.—This paper by John W. T. Van Erp was published in November, 1950, as *Proceedings-Separate No. 42*. The numbering of footnotes and equations in this Separate is a continuation of the consecutive numbering used in the original paper.

[9] Structural Design Engr., Sargent & Lundy, Engrs., Chicago, Ill.

[10] Prof. of Civ. Eng., George Washington Univ., Washington, D. C.

[11] "What Aerodynamics Can Teach the Civil Engineer," by W. Watters Pagon, *Engineering News-Record*, Vol. 112, March 15, 1934, p. 348.

oblique angles of incidence. The resultant wind force does not, in general, pass through the center of twist of the structure as viewed in the plan. Therefore, the structure is subjected to a torsional moment about a vertical axis through its center of twist. The amount of the torque depends on the height-to-width ratio and length-to-width ratio of the building, as well as on the angle of incidence of the wind, but tests have shown that the torque is not negligible even for structures of quite ordinary proportions.[12,13,14] For long and narrow buildings the twisting moment may be disastrously large. For example, it has been suggested that the mode of failure of the Meyer-Kiser Building in the Miami (Fla.) hurricane of 1926 confirms the existence of such moments.[15,16]

Torsional moments of considerable magnitude must certainly be considered in the design of tall buildings. These moments will vitally affect the design of the wind bracing in mill or industrial buildings. Consequently it is rather difficult to understand why the writers of standards have ignored the condition of oblique incidence of wind.

It appears to the writer that an opportunity exists for the author to present a summary of provisions specifying the location of the resultant wind force as dealt with in various standards. The information should prove to be of great value to engineers concerned with the design of structures. It is impossible to estimate the waste of material on one hand and the possible reduction in presumed factors of safety on the other that may be caused by the use of unrealistic standards for wind loading. The annual cost is certainly heavy. When there is a shortage of building materials, any information that contributes to more rational design of structures is welcome.

It may be that available data are too meager to permit the formulation of standard provisions for twisting moments caused by oblique wind. If such is the case, it would appear that this is a fit subject for experiment on a well-chosen series of model shapes. Some use could be made of published results that are presented in the form of pressure distributions, for pressure distributions may be translated into twisting moments by numerical integration methods.[17,18]

The investigation of a limited number of shapes should provide the information needed to permit the formulation of standard provisions for buildings of the usual types and proportions. It is always expected that special model tests will be required for structures of unusual shape or dimensions.[19]

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[12] "Wind Pressure on Buildings," by J. O. V. Irminger and Chr. Nøkkentved, *Ingeniørvidenskabelige Skrifter*, A Nr. 23, Copenhagen, Denmark, 1930.

[13] *Ibid.*, A Nr. 42, 1936.

[14] "Wind Pressures on Structures," by Hugh L. Dryden and George C. Hill, *Scientific Papers of the U. S. Bureau of Standards*, Vol. 20, 1926, p. 696.

[15] "Wind-Tunnel Studies Reveal Pressure Distribution on Buildings," by W. Watters Pagon, *Engineering News-Record*, Vol. 113, 1934, p. 814.

[16] "Elementary Stress Analysis," by Phillip E. Soneson, Pitman Publishing Corp., New York, N.Y., 1949, p. 142.

[17] "Wind Pressures on Structures," by Hugh L. Dryden and George C. Hill, *Scientific Papers of the U. S. Bureau of Standards*, Vol. 20, 1926, p. 714.

[18] "Wind Pressure on a Model of a Mill Building," by Hugh L. Dryden and George C. Hill, *Journal of Research*, U. S. Bureau of Standards, Vol. 6, 1931, p. 735.

[19] "Aerodynamics of the Perisphere and Trylon at World's Fair," by A. Klemin, E. B. Schaefer, and J. G. Beerer, Jr., *Transactions*, ASCE, Vol. 104, 1939, p. 1449.

FRANCIS L. CASTLEMAN, JR.,[20] M. ASCE, AND ARON L. MIRSKY,[21] ASSOC. M. ASCE.—The School of Engineering of the University of Connecticut (Storrs, Conn.), in the course of setting up a research program on the action and effect of the wind on structures, made a critical survey of literature on the subject. Although experimental results of this research project are not available, it is believed some of the results of the literature search might prove of interest and emphasize some of the differences of opinion encountered.

There appears to be no definite agreement among the various writers on scale effect (Reynolds number). (In this connection it is pertinent to mention that the absence of scale effect is equivalent to zero viscosity. This results in a Reynolds number of infinity and not unity as stated by the author in the section on "Shape Coefficients.") Early investigators tended to discount scale effect in the case of structures with sharp edges, such as ordinary buildings, bridges, and other common engineering structures, as either absent entirely or negligible. However, later investigations seemed to indicate that scale effect may be of some importance in such cases, but the diversity of opinion is still great, and as yet there appears to be no critical standard (other than personal opinion) to indicate whether scale effect may be neglected or not.

G. Eiffel,[22] incidental to his studies on hangars, investigated three geometrically similar models with peaked roofs and with dimensions in the ratios of 400:50:8. Within the limits of precision of his measurements he reported identical pressure distributions on all three models and concluded there was no scale effect; he then applied that conclusion to hangars with rounded roofs. Apparently, also, he did not attempt to verify his conclusions by varying the wind velocity (hence, the Reynolds number) during the tests on any one model.

C. Nøkkentved[23] and J. Irminger[13] have shown that the relationship between the slope of the leading (windward) vortex sheet and the slope of the windward roof determines whether there is pressure or suction on the roof surface. They have also shown that the slope of the windward vortex sheet, in turn, is a function of the roughness of the ground surface to the windward of the structure (prototype or model). Consequently, the slope is a function of the Reynolds number as well as of the height of the structure. A consequence of this is that each structure or model has a critical height. In the case of Mr. Eiffel's models the critical height was so much larger than the height of the largest model that the effect was apparently not evident. Had a larger range of model ratios been investigated, the effect would undoubtedly have been recognized.

In an earlier publication,[12] however, Messrs. Nøkkentved and Irminger were of the opposite opinion, namely, that the extent of the vortex region in the case of sharp-edged bodies is independent of wind velocity, that is, that scale effect does not exist for such bodies.

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[20] Dean, School of Eng.; Prof. of Civ. Eng., Univ. of Connecticut, Storrs, Conn.

[21] Instr. in Civ. Eng., Univ. of Connecticut, Storrs, Conn.

[22] "Nouvelles recherches sur la résistance de l'air et l'aviation faites au laboratoire d'Auteuil," by G. Eiffel, Dunod et Pinat, Paris, 1914, pp. 283–302.

[23] "Wind Pressure on Buildings. An Investigation into the Influence of the Size of the Models," by Chr. Nøkkentved, *Publications*, International Assn. for Bridge and Structural Eng., Vol. 2, 1933, pp. 257–264.

The conclusions of Hugh L. Dryden and George C. Hill[14,24,25,26] follow the same pattern as those of Messrs. Irminger and Nøkkentved. At first Messrs. Dryden and Hill discounted scale effect, but later they reached the conclusion that errors due to neglecting it were small and commented that until such belief has been confirmed by full-scale experiments on actual structures, results from model tests could not command the full confidence of engineers engaged in the design of buildings. To date, the writers have been able to find no such verification in the literature.

In regard to the influence of neighboring structures C. L. Harris[27] found a slightly larger (but still minor) scale effect when including models of neighboring buildings in the experiment. A. Bailey and N. Vincent[28] found a definite scale effect, such as Mr. Bailey[29] himself had found in earlier experiments. In both sets of experiments it was noted that the scale effect was particularly evident on the leeward sides of the structures. Such suction effect of the wind, although found in experiments as far back as the 1890's, has only recently been recognized by the engineering profession.

In 1950 M. R. Horne[30] concluded that sufficient work had been done on models to predict the steady wind pressure on any normally shaped structure provided that some unspecified allowance be made for scale effect. The nature of this scale effect requires further investigation, but sufficient data are at hand (he does not specify where) to indicate what allowance should be made for it.

From a review of the experimental data, the theoretical analyses, and the speculations recorded in the literature, only a minor fraction of which has been cited, it may be seen that as yet there is no pat answer to the question of the existence of a scale effect and whether it is of practical importance in the case of ordinary engineering structures. The writers do not pretend to know. From the conflicting evidence so far presented, one of the writers tends to the opinion that for conventional sharp-edged structures, scale effect is probably not a critical factor, and the other is highly doubtful. Both writers, however, are firmly of the opinion that the existence and importance of scale effect remains to be proved by experiment.

S. K. GHASWALA,[31] Assoc. M. ASCE.—An interesting sidelight on wind-load analysis has been presented in this paper which represents one of the few attempts to chart out the subject from international standards. It is for this reason that the paper should be studied by many workers in the field.

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[24] "Wind Pressure on Circular Cylinders and Chimneys," by H. L. Dryden and George C. Hill, *Journal of Research*, U. S. Bureau of Standards, Vol. 5, 1930, pp. 657–658.

[25] "Wind Pressure on a Model of a Mill Building," by Hugh L. Dryden and George C. Hill, *Journal of Research*, U. S. Bureau of Standards, Vol. 6, 1931, p. 755.

[26] "Wind Pressure on a Model of the Empire State Building," by Hugh L. Dryden and George C. Hill, *Journal of Research*, U. S. Bureau of Standards, Vol. 10, 1933, p. 495.

[27] "Influence of Neighboring Structures on the Wind Pressure on Tall Buildings," by C. L. Harris, *Journal of Research*, U. S. Bureau of Standards, Vol. 12, 1934, pp. 107–108.

[28] "Wind-Pressure on Buildings Including Effects of Adjacent Buildings," by Alfred Bailey and Noel D. G. Vincent, *Journal*, Inst. of Civ. Engrs., Vol. 20, 1943, pp. 264 and 269.

[29] "Wind-Pressures on Buildings," by Alfred Bailey, *Paper 139*, Inst. of Civ. Engrs., 1933.

[30] "Wind Loads on Structures," by Michael Rex Horne, *Journal*, Inst. of Civ. Engrs., Vol. 33, 1950, pp. 158–159.

[31] Chartered Engr., "Edena," Queen's Road, Fort., Bombay, India.

Wind is motion of the air caused by gravity, by deflective forces due to the earth's rotation (termed Coriolis forces), and by centrifugal forces due to curvature of the wind path. It is evident that an appraisal of its exact effect is not simple as this effect is dependent on several factors that in themselves are further functions of other variables, such as friction and viscosity. The flow of air at any period is never smooth but is subject to fluctuations. When sudden and relatively brief, these fluctuations represent gusts. Gustiness or atmospheric turbulence is of great importance in structural design and is accompanied by so many variations of velocity, temperature, and humidity that no completely satisfactory theory exists as to why it arises and how it proceeds.[32] It is believed, however, that gusts are caused mainly by the growth of eddies due to mechanical obstacles, irregularities of ground, local pressure differences, deflection around objects, and vertical thermodynamic interchange, or a combination of the above causes.[33] The most complete and accurate observations and records of meterorological factors to be used in appraising wind velocity and gusts have been given by H. Ferrington in England[34] and R. H. Sherlock, M. ASCE, in the United States.[35] These studies indicate that the maximum hourly mean wind is the most appropriate value to be considered in design and should be assumed as the steady pressure acting on a structure. On this force should be superimposed a periodic pressure produced by gusts and recorded over the same period as the hourly mean wind. An examination of these results would have added much to the value of the paper.

It was Sir Isaac Newton who first evolved the algebraic expression for wind pressure, giving it as equivalent to the square of the wind velocity. This expression was used by many French engineers for designing structures at the beginning of the twentieth century. These expressions were later replaced by the now familiar concept of E. N. Duchemin and J. S. Hutton. Unfortunately these formulas are not accurate, as demonstrated by recent aerodynamic research and wind-tunnel experiments[36] that clearly reveal the lack of consideration for wind pressure on the leeward side of the structure. Pioneering work on wind-tunnel analysis that threw new light on the subject was carried out by J. O. V. Irminger in Copenhagen. His work was continued by many other prominent workers in the field.[33]

The writer fully agrees with the author that the subject of gusts is still in a nebular state of development. The science of wind-pressure analysis and design can be brought to perfection only when the fundamental dynamic character of wind loads is expressed as static equivalents to give simple and reliable data for the designing engineer.

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[32] "Physical and Dynamical Meteorology," by David Brunt, Cambridge University Press, Cambridge, England, 1939.

[33] "Aerodynamic Aspects of Civil Engineering," by S. K. Ghaswala, *Civil Engineering and Public Works Review*, London, England, September, 1950, pp. 586–589; October, 1950, pp. 646-649; November, 1950, pp. 725–727.

[34] "Wind Loads on Buildings," by H. Ferrington, *The Structural Engineer*, December, 1943, p. 497; January, 1944, p. 15.

[35] "Gust Factors for the Design of Buildings," by R. H. Sherlock, *International Association for Bridge and Structural Engineering*, Vol. 8, 1947, p. 207.

[36] "The Function of Aerodynamics in Civil Engineering," by S. K. Ghaswala, *Journal of the Inst. of Engineers*, India (publication pending).

HERBERT S. SAFFIR,[37] Assoc. M. ASCE.—Detailed description of wind-load standards in European countries should prove of value in formulating wind-load requirements for building codes in the United States. The compilation of velocity pressures at different heights and wind-load coefficients for different shapes of buildings can serve as a useful guide in revising building codes and for use in structural design. Because of the dynamic character of the loading and the probability of occurrence of such loading, it is doubtful if wind-load standards can ever be refined enough to agree with actual conditions.

The idea of frequency differential, introduced in the specified basic velocity pressures in the Netherlands standard, is mentioned. It is stated that each range has been subgraduated according to geographic locality. The writer believes that a similar plan should be established for different regions in the United States. Various wind loadings could be specified in standard building codes and standard design specifications for varying conditions throughout the entire country. The writer has in mind a map comparable to the velocity pressure map prepared by the United States Bureau of Standards from United States Weather Bureau data.[38] A map of this type could be used for structural design in localities not covered by building codes or by local building code committees writing and revising building codes. The shape and exposure of the structure and the probability of gust velocities would be other factors entering into the choice of a design wind load for a particular structure.

Shape coefficients, such as those shown for open sheds in Fig. 4, are of value from a designer's viewpoint. Specifications have been drafted to account for the shape effect, and a typical provision is quoted here:[39]

> "The effect of shape of irregular or unusual roofs may be determined by wind tunnel or equivalent tests. In determining the effect of shape, the assumed wind velocity shall be the maximum average for five (5) minute period shown in the records of the U. S. Weather Bureau during the past fifteen (15) years, and the prescribed wind forces shall be modified accordingly."

The writer notes that coefficients for circular arc roofs are not mentioned in the paper. Are shape coefficients for such types of roofs omitted because of the scale effect in evaluating test results?

THEODORE B. RIGHTS,[40] Assoc. M. ASCE.—The author is to be congratulated for bringing a greater realism into a subject that some engineers consistently refuse to study objectively. Many engineers concern themselves only in what the "code" says, with no further analysis. The subject of wind loads is a serious matter, as many who experienced the wind storm along the eastern seaboard on November 25, 1950, can testify.

In the introduction the author speaks of "* * * cases of damage from wind recur far too frequently." There should be an "autopsy" of wind failures for

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[37] Asst. County Engr., Dade County Eng. Dept., Miami, Fla.

[38] "American Standard Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," *Miscellaneous Publication M179*, U. S. Bureau of Standards, Washington, D. C., 1945.

[39] "Basic Building Code," Building Officials' Conference of America, Inc., New York, N. Y., 1950 Ed., Section 715.4, p. 125.

[40] Cons. Engr., Roselle, N. J.

bridges and buildings. Only in cases of large structures, such as the Tacoma Narrows Bridge (Wash.) or the Mississippi River Bridge at Chester, Ill., are investigations made and the findings published. The small structure that blows down without killing anyone is only reported in the local paper by such comment as: "The high winds of yesterday blew down a section of the walls of the new A Manufacturing Company building." Even this small item is omitted from the paper if A Manufacturing Company has a publicity agent who sees that unfavorable news is omitted from the papers. Building inspectors should be compelled by law to submit investigation reports of failures and pertinent data to a board for further analysis. Since the engineering profession has no money to set up such a board, and since it also dislikes to advertise its mistakes, this board should be set up by the state. The main purpose of such a board would be to study the submitted reports and to make recommendations that would enable engineers to design their structures realistically to resist wind pressure.

As stated by the author, there are few codes in the United States that specify drag or suction; yet only a short time ago, a case was brought to the writer's attention of a building in Canada that had part of its steel roof deck ripped off. The suction, or the inside pressure, was so great that steel sheets tore around the welds which fastened them to the purlins. In the same building, a rolling steel door was blown out and rolled down the tracks. Isn't it about time that officials realize this is a serious problem and try to do something about it?

In June, 1946, J. C. Early asked about the analysis of slender angle girts.[41] So far as the writer knows there has been no answer to his questions. Perhaps the reason that girts do not fail is that structural engineers do not find that the actual wind load is as great as the design load. If this is so, why doesn't the designer use lighter loads for the design of wind bracing and uplift?

Since there are many more low buildings designed than the high, or skyscraper, type, engineers should study and have the data of wind effects on small buildings. Several excellent studies have been made on tall buildings. Perhaps someone will study the small, or warehouse type, building less than 60 ft high.

It seems peculiar that the author referred to excellent articles[4,5] published as long ago as 1934 and 1935. Are there no later articles on this subject? In succeeding years the engineering profession should have collected more data on this difficult subject.

JOHN W. T. VAN ERP.[42]—The various discussions have introduced many more aspects of the subject than those covered in the paper, notably those aspects relating to observed data and phenomena and their interpretation into a set of design specifications.

Mr. Rogers is correct in his statement that resonance is a factor of prime importance, especially for slender structures of little mass and rigidity, such as the one mentioned in his example. Even single wind gusts without any cumulative resonance effect cause a greater deflection on these structures than on structures of great mass and rigidity, such as a building. For these

[41] "Analysis of Slender Angle Grits," by J. C. Early, *Civil Engineering*, Vol. 16, 1946, p. 267.

[42] Associate Engr., Trygve Hoff and Associates, Cleveland, Ohio.

latter, however, the period of vibration is many times as large as that of any pulsating wind load, so the writer still maintains that any chance of resonance is extremely remote. Although an exact determination of the period of such a structure by theoretical methods can hardly be arrived at, empirical formulas that give an answer exist. A pertinent paper,[43] for instance, gives:

$$T = c\frac{H}{\sqrt{b}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

in which T is the period in seconds; H is the height in feet; b is the width in feet in the direction of vibration; and c is a coefficient varying between .05 and .06 for most buildings. Another element that enters into the picture is that slender structures presenting only a small cross-sectional area perpendicular to the direction of the wind (whose area, in other words, is equal to or smaller than that of the wind gust) are more sensitive to a pulsating wind load. A design for such a structure, based on the standard velocity-pressure loads alone, might be too light. In connection with this subject reference is invited to the section on "Velocity Pressure" and also to curve IV in Fig. 1. On this basis it is recommended that for structures of small cross-sectional area perpendicular to the wind, say 200 sq ft or less, the design wind load should be increased by 10%.

Mr. Walther refers to the possibility of a phenomenon, the existence of which has not been conclusively proven, to the best knowledge of the writer. Here another subject for further research is clearly indicated. In case, however, the definite existence of such an eccentricity of the wind load resultant at certain angles of obliquity in the horizontal plane would be proven, it seems appropriate that this factor should be taken into consideration in conjunction with the specification of maximum velocity pressures for certain orientations, depending on geographical location. A velocity pressure map[44] should, therefore, be complemented by compass cards, indicating orientation of the maximum velocity pressures at key locations.

In their discussion Mr. Castleman and Mr. Mirsky present a comprehensive review of experimental and theoretical analyses on the existence of scale effect. The general conclusion still seems to be that the existence of scale effect is, to say the least, doubtful. Thus, there seems to be no reason why data derived from small-scale tests should not be incorporated into design specifications, the exposition of which has been the chief purpose of the paper.

It is evident from Mr. Ghaswala's discussion that the paper has only partially covered the available knowledge in this field. Apparently the engineering knowledge available in print is already much more extensive than that covered by the writer, apart from the sphere outside of his necessarily limited confinements.

The aim to strive for in a perfect set of wind-load standards should be a comprehensive coverage of all possible loading conditions, and the writer is

[43] "Lateral Forces of Earthquake and Wind," by a Joint Committee of the San Francisco, Calif. Section, ASCE, and the Structural Engineers Association of Northern California, *Proceedings-Separate No. 66*, ASCE, Vol. 77, April, 1951.

[44] "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," *A58, 1-1945*, American Standards Association, New York, N. Y., 1945, Fig. 2, p. 20.

optimistic enough to believe that this can be achieved, using a not-too-unwieldy set of standards. The hurricane of November 25, 1950, on the east coastal area provided a very tangible demonstration of the general lack of proper knowledge of the effects of wind load. The recorded wind velocities indicated that maximum velocity pressures of about 25 lb per sq ft were reached, an excess of only 25% over specifications of the local code. The damage to one of the newest tall buildings, running well into five figures, probably indicates the existence of such a phenomenon as discussed by Mr. Walther. The eccentricity of the wind load, resultant at oblique angles of wind direction, should be particularly noticeable with an oblong-shaped plan, such as the one of this building. Furthermore the ubiquitous occurrence of suction on the leeward sides was demonstrated by many broken shop windows on those sides.

For wind loads on arched roofs, the shape coefficients given in the paper are of sufficient accuracy to govern design loads without consideration of any scale effect. The given shape coefficients would indicate considerable suctions over the entire roof area for flat curvatures of the arch, corroborated, for instance, by early wind-tunnel tests on models of gas holders with a dome top. The writer fully agrees with the suggestion made in the discussion by Mr. Rights that wind loads up to now have definitely been treated as an unimportant factor in design load. Consequently, not enough importance is being attached to the multitude of observations of the smaller everyday storm damages that could otherwise, by proper coordination and classification, furnish an elaborate basis for the perfection of wind-load standards. Finally, it may be stated that, in general, a more articulate and specific set of wind-load standards than those available is desired. The writer hopes that the cited examples indicate the way in which these standards can be developed, on the basis of abundant experimental and theoretical data, into a versatile expedient at the service of the designing engineer.

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